Journée parrainée par

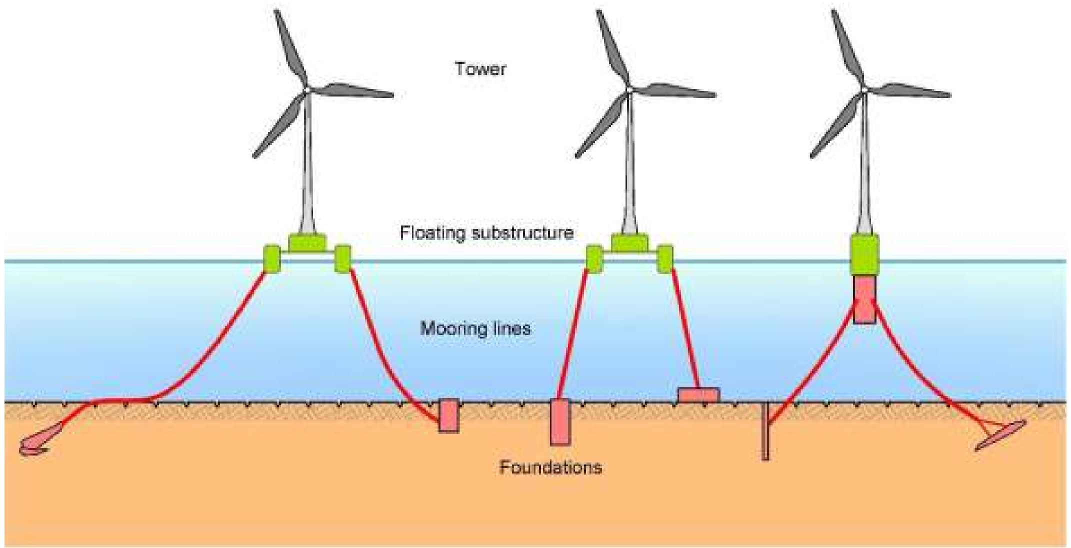
Ancres draguées et ancres plaques

Daniel Orejuela (Subsea 7)

Floating Wind Farm
Drag Anchors and Plate Anchors Recommendations

Topics:

- Type of Anchors – General description
    - Plate Anchors – Drag Embedded anchors
- Penetration predictions – Drag Embedded anchors
- Anchor line equations
- Drag Embedded Anchors kinematic
- Drag Embedded Anchors in sand and high strength Clays
- Characteristic resistance of Fluke anchors
- Post Installation effects
- Installation tension and proof tests



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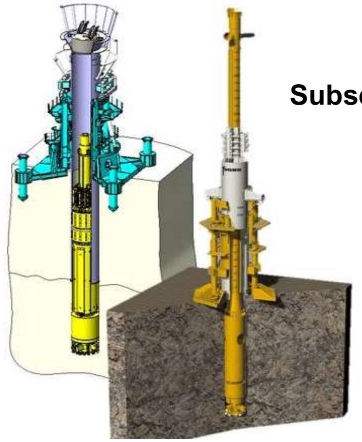
Drag Anchors and Plate Anchors Recommendations

Type of anchors

- **Anchor Piles :**
  - **Driven/vibro Piles**
  - **Drilled and Grouted Piles**
  - **Dynamically installed piles (Torpedos)**

Subsea Drilling



Courtesy of Fugro drilling services

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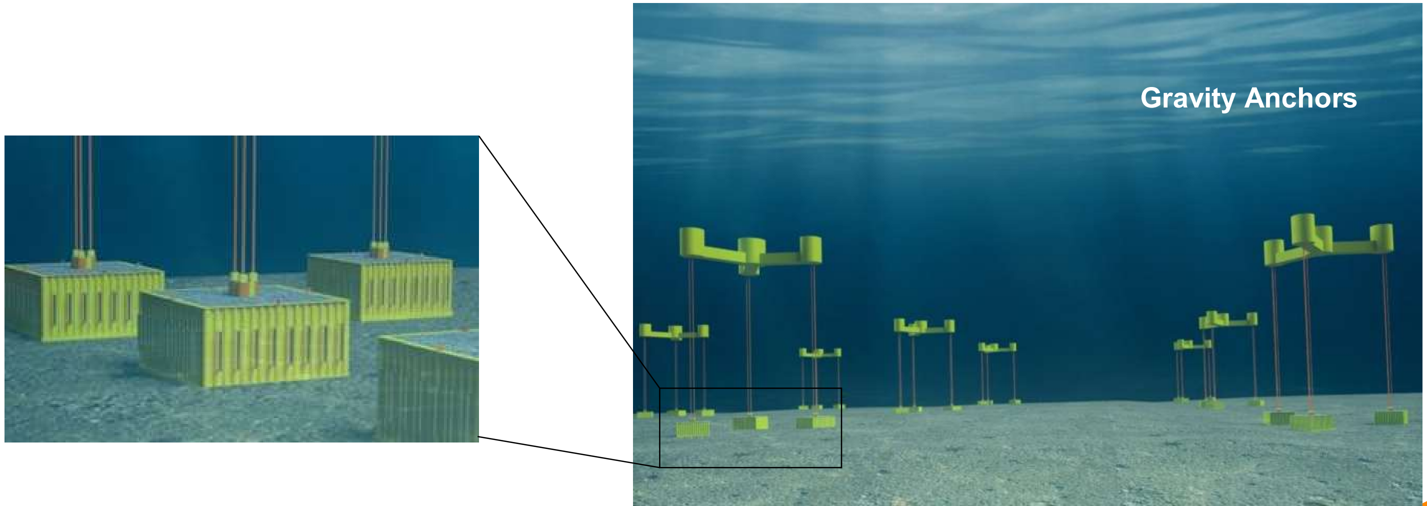
Drag Anchors and Plate Anchors
Recommendations

Type of anchors

- Suction Anchors
- Gravity Anchors



Source: Offshore wind design AS

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Drag Anchors and Plate Anchors Recommendations

Type of anchors

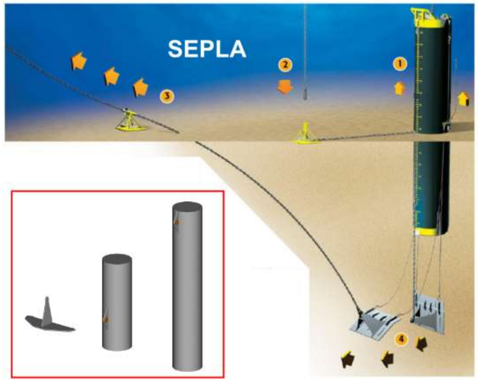
- **Plate Anchors:**

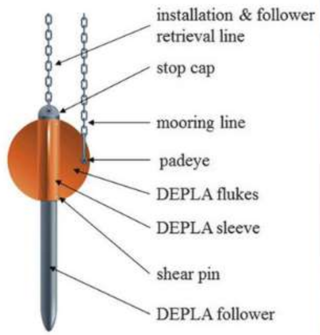
  Push-in Plate Anchors

  Suction Embedded Plate Anchor (SEPLA)

  Dynamically Embedded Plate Anchor (DEPLA)

INTERMOOR





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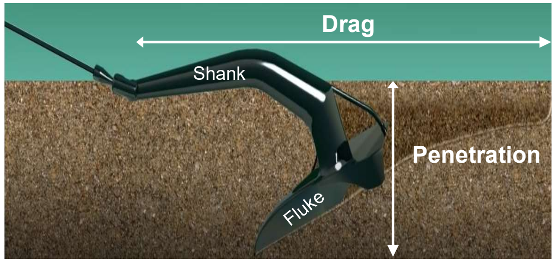
Drag Anchors and Plate Anchors Recommendations

Drag – Embedment Anchors (DEA)



Fluke Anchors

- HHP anchors
- 3x4 to 6x9m – 5t to 50t (i.e. ballasted)
- Limited uplift resistance

Vertical Loaded Anchors (VLA)

- Tension on the line is redirected to be perpendicular to the plate
- Shear Pin
- Require deep burial
- 5 to 30m² fluke area

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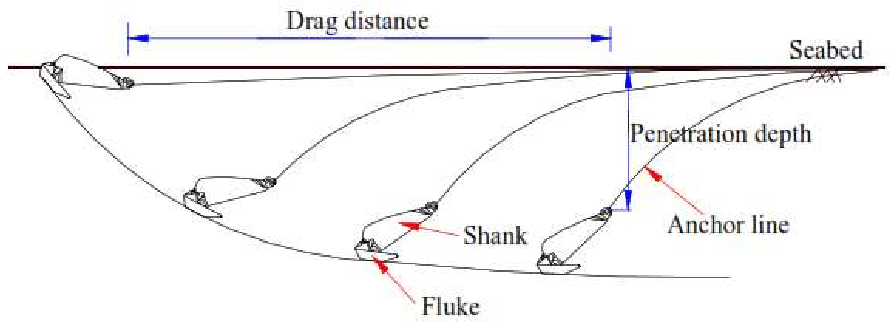
Drag Anchors and Plate Anchors
Recommendations

Drag Embedment Anchor – trajectory predictions & UHC

- **The penetration and self-burial of a fluke anchor into the seabed is a complex soil structure interaction mechanism**
- **The initial angle during anchor setting is a governing parameter**
- **Trajectory & UHC prediction methods:**
    - Empirical (Based on manufacturer charts)
    - Analytical approaches (i.e. limit equilibrium and Plasticity)
- **Predictions are particular challenging in layered soils**
- **Chain forerunner / soil interaction influences the anchor trajectory**



Drag anchor trajectory in Clay[1]

[1] Upper Bound Analysis for Drag Anchors in soft clay – Kim et al. (2005)

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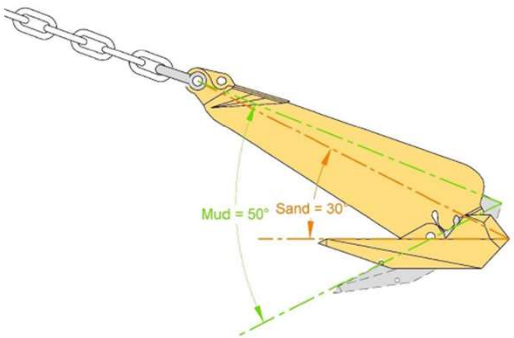
Drag Anchors and Plate Anchors
Recommendations

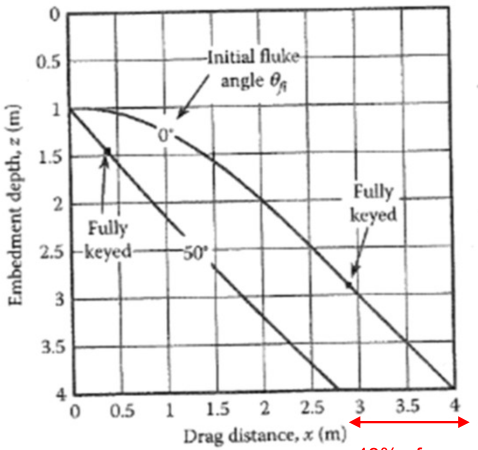
Drag Embedment Anchor – Penetration/trajectory predictions

Effect of the initial angle into the anchor trajectory

- Optimal initial fluke angle for setting stage

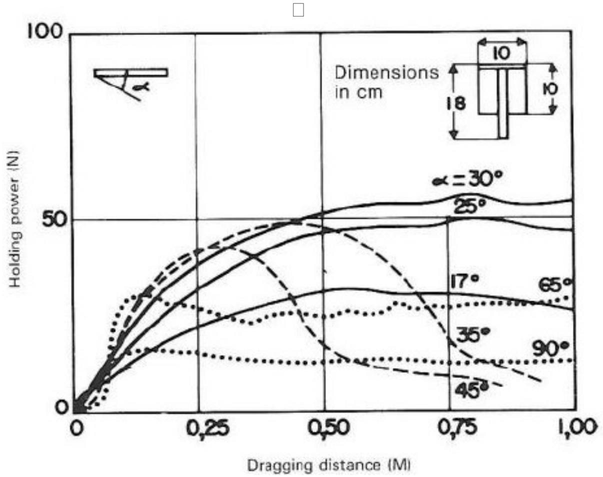


Effect from initial fluke angle in clay



+48% of more drag needed

Behaviour of a scale model anchor in a sand bed (α=40°). Effect of fluke angle



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Drag Anchors and Plate Anchors Recommendations

Drag Embedment Anchor – Penetration/trajectory predictions

Empirical predictions

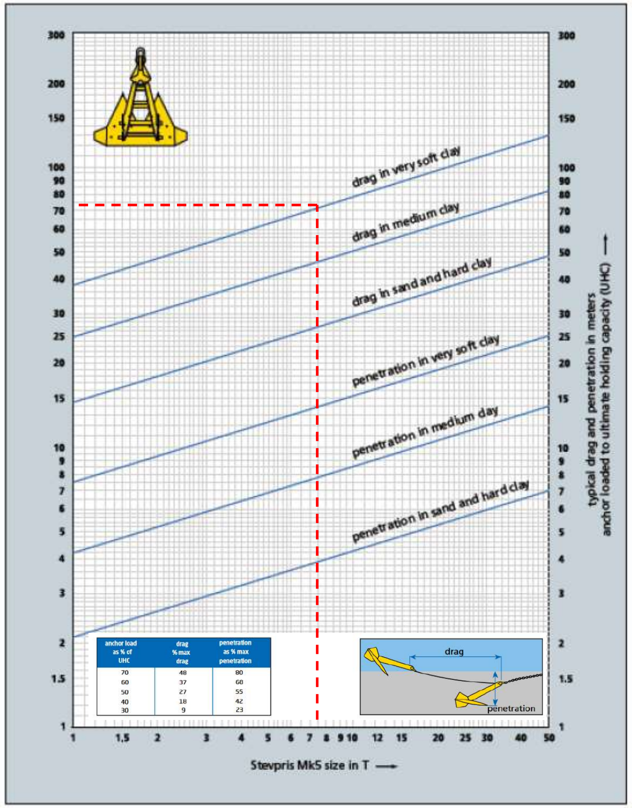
- Based on anchor manufacturer charts
- Recommendations from codes
  - ISO, API, (Based on NEL)
- Charts are provided for generic soil conditions and not site specific

NEL: (Naval Civil Engineering Laboratory)

Anchor type	Normalized fluke tip penetration (Fluke lengths)	
	Sands/stiff clays	Mud (e.g. soft silts and clays)
Stockless	1	3[a]
Moorfast Offdrill II	1	4
Boss Danforth Flipper delta GS (Type 2) LWT Stato Steyfix	1	4 ½
Sevpris MK III Bruce FFTS MK III Bruce TS Hook Stevmud	1	5

[a] Fixed fluke stockless.

BS-EN-ISO 19901 -7 :Station keeping systems for floating offshore structures and mobile offshore units – Estimated Maximum fluke tip penetration



Example of Vryhof chart for drag/embedmet predictions

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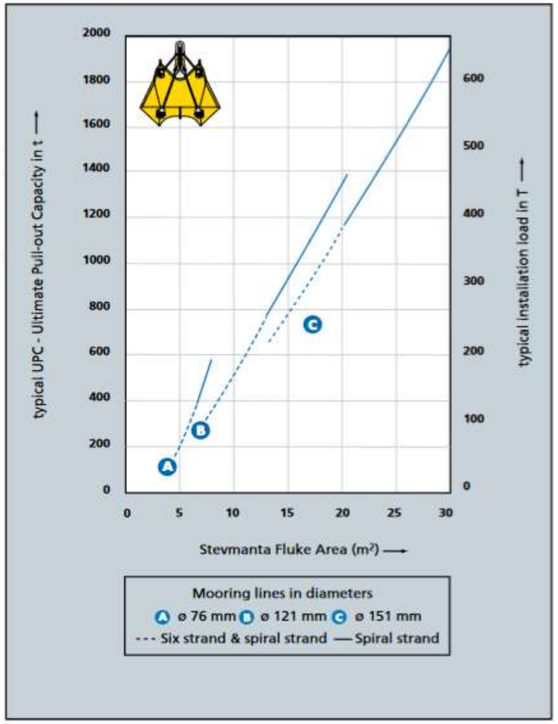
Drag Anchors and Plate Anchors Recommendations

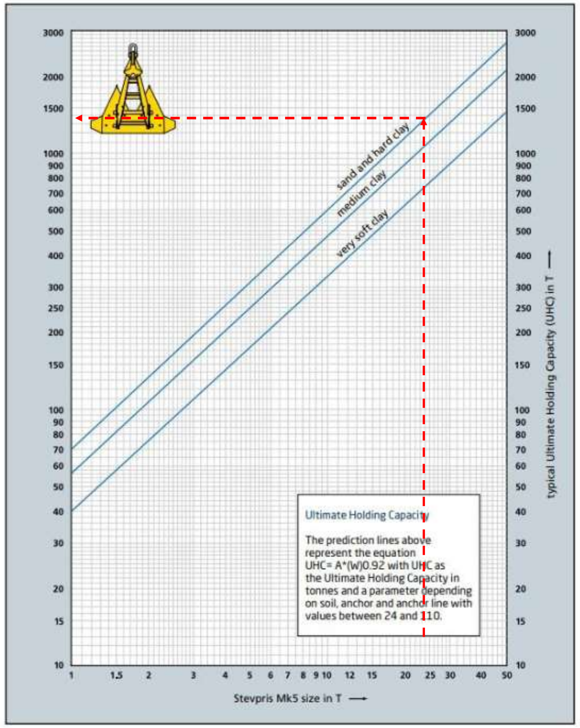
Drag Embedment Anchor – UHC empirical predictions

Empirical predictions

- Based on anchor manufacturer charts
- Recommendations from codes
  - ISO, API, (Based on NEL)
- Charts are provided for generic soil conditions and not site specific
- General practice is to consider :
  - A penetration not exceeding 60% of the maximum penetration; or
  - A resistance not exceeding 60% of the ultimate resistance.



Design chart Stevmanta VLA – (vryhof)



Design chart Stevpris MK5 – (vryhof)

NEL: (Naval Civil Engineering Laboratory)

UHC : Ultimate Holding Capacity

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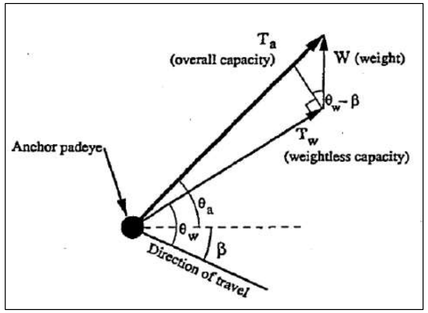
Drag Anchors and Plate Anchors Recommendations

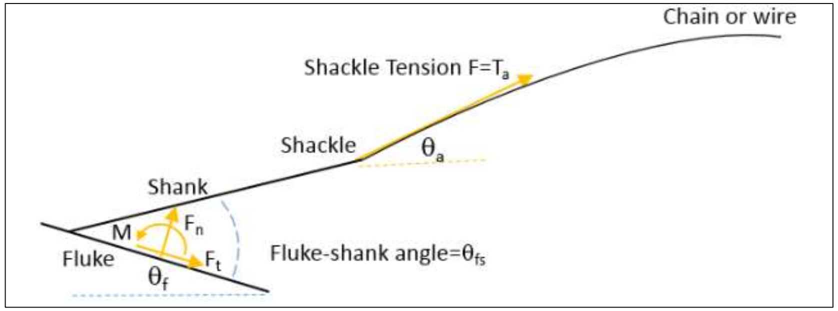
Drag Embedment Anchor – Penetration/trajectory predictions in CLAY

- **Analytical approaches**
  - **Based on Limit Equilibrium:**
    - **Neubecker and Randpolph***
    - DNV (DIGIN software): (DNV-RP-E301)
  - **Based on Plasticity limit models**
    - O'Neil et al.
    - **Aubeny and Chi***
- **Anchor line equations**
  - Integration of DEA trajectory & Anchor line equation

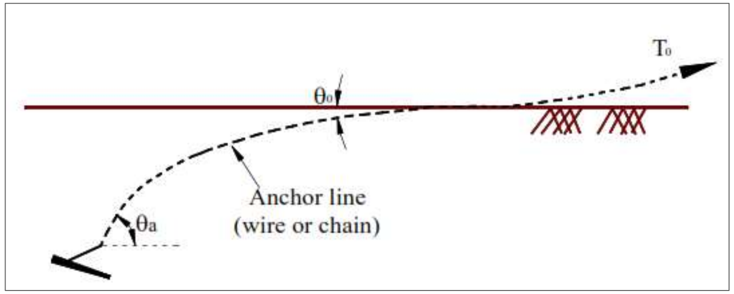
** General principles for drag anchors in Clay provided in "Recommendations for planning and designing anchor foundations of floating wind turbines Appendix D" CFMS (2024)*



Equilibrium of forces model – Neubecker & Randolph



Analytical method - simplified model for drag anchor equilibrium – Aubeny et al



Reverse catenary of anchor line (forerunner)

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Recommendations

Anchor line equations - Clay

Anchor line on the seabed (lying line)

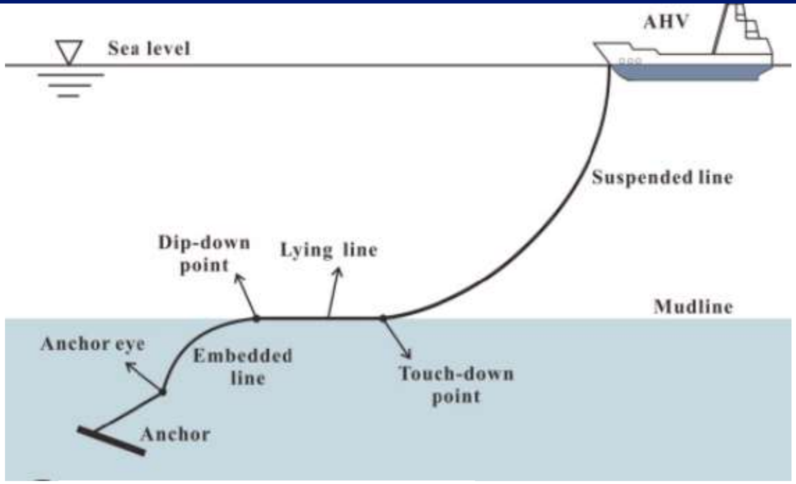
- No uplift during installation
- Seabed friction

$$\Delta R_{fric} = f.L_s = \mu \cdot W_l' \cdot L_s$$

μ	=	coefficient of seabed friction
f	=	seabed friction per unit length of the line [kN/m]
W_l'	=	submerged weight per unit length of anchor line [kN/m]
L_s	=	length of the slack portion of the line on the seabed [m]

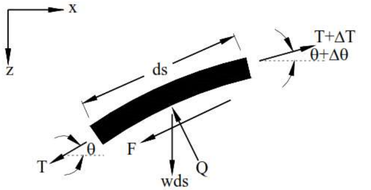
Table C.1: Coefficient of seabed friction in clay from DNV-RP E301 (2021)

Seabed friction $\mu_{starting}$	Lower bound	Default value	Upper bound
Wire	0.1	0.2	0.3
Chain	0.6	0.7	0.8



Anchor line embedded in the soil

- From dip-Down point to anchor shackle
- Reverse catenary shape: Numerical iteration – Boundary conditions (known T at Dip-down, shackle z (m))
- Recommended values of En, Et, Nc & α (DNV-RP-E301) for wire/chain
- Simplified method proposed by Neubecker & Randolph (W'$_l$ neglected) $T_a\left(\theta_a^2 - \theta_0^2\right) = 2zE_nN_cb\left(s_{u0} + k\frac{z}{2}\right)$



Force equilibrium element of chain– Vivarat et al

$$\frac{dT}{ds} = F + W'_l \sin\theta$$

$$T\frac{d\theta}{ds} = -Q + W'_l \cos\theta$$

$Q = E_n \cdot b \cdot q$ normal to chain

$F = E_t \cdot b \cdot f$ parallel to chain

$$q = N_c \cdot s_u$$

$$f = \alpha \cdot s_u$$

Floating Wind Farm
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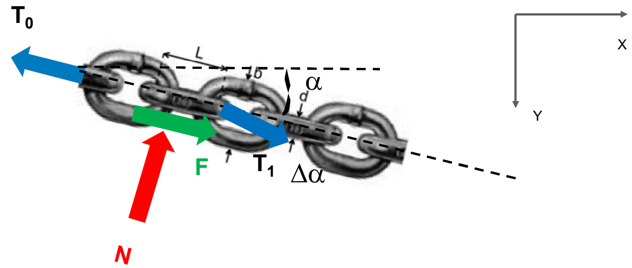
Anchor line equations – Non-Cohesive soils

Mortensen (2015)

$F = N \cdot \alpha_{sand}$ $N = d \cdot L \cdot A_{sand} \cdot (0.5\gamma' \cdot d\, A_{sand} + N_q \gamma' \cdot z)$ (Bearing capacity strip foundation)

Line	A_{sand}	α_{sand}
Wire	1.0	$\tan\phi'$
Chain	b/d (~3.4)	0.5

Inverse catenary shape: Numerical iteration – Boundary conditions (known T at Dip-down, shackle z (m))



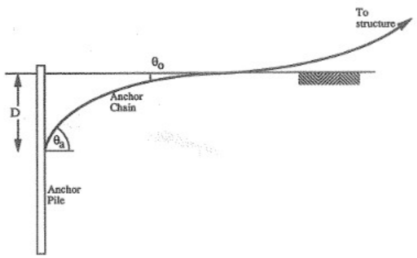
Force equilibrium element of chain– Mortensen (2015)

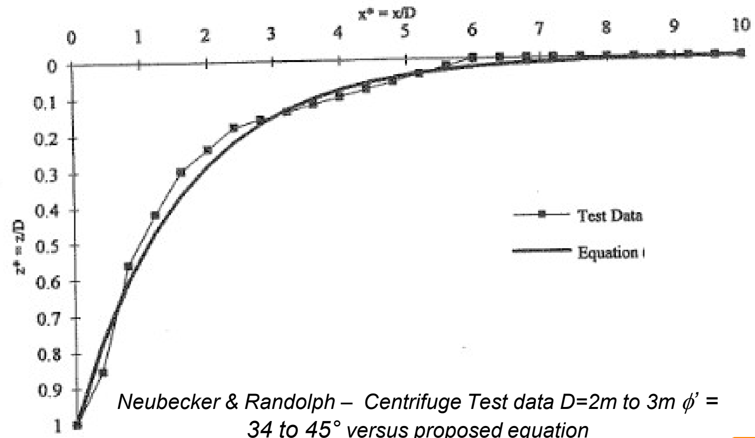
Neubecker & Randolph (1995) :

- Exponential relationship to derive the reverse catenary

$$z^* = e^{-X^* \theta a}$$

- Good approximation for soils with proportional bearing resistance to depth





Neubecker & Randolph – Centrifuge Test data D=2m to 3m ϕ' = 34 to 45° versus proposed equation

DEA kinematic and anchor line equation in clay

- **Aubeny and Chi (2010)**

Kinematic of the anchor:

Angular velocity of the fluke: $\dot{\beta} = \lambda \frac{\partial f}{\partial N_m}$

Tangential velocity : $v_t = \lambda \frac{\partial f}{\partial N_t}$

Normal velocity $v_n = \lambda \frac{\partial f}{\partial N_n}$

Anchor holding capacity

$$f = \left(\frac{|c_1| N_e}{N_{n,\max}} \right)^q + \left[\left(\frac{|c_3| N_e}{N_{m,\max}} \right)^m + \left(\frac{|c_2| N_e}{N_{t,\max}} \right)^n \right]^{\frac{1}{p}} - 1 = 0$$

$$N_n = N_{e0} C_1$$
$$N_t = N_{e0} C_2$$
$$N_m = N_{e0} C_3$$

N_{e0} calibrated from field measurements (ranges 4.4 to 9)

m,n,p,q = interaction coefficients considered as $m = 1.56$, $n = 4.19$, $p = 1.5$ and $q = 4.43$ (Murff et al. 2005)

Ratio Normal /tangential translation

$$R_{nt} = \frac{v_n}{v_t} = \frac{\left(\frac{N_{tmax}}{N_{nmax}}\right)\left(\frac{pq}{n}\right)\left(\frac{|N_n|}{N_{nmax}}\right)^{q-1}}{\left[\left(\frac{|N_m|}{N_{mmax}}\right)^m + \left(\frac{|N_t|}{N_{tmax}}\right)^n\right]^{\frac{1}{p}-1} \left(\frac{|N_t|}{N_{tmax}}\right)^{n-1}}$$

Anchor line equation (Neubecker & Randolph)

$$T_a\left(\theta_a^2 - \theta_0^2\right) = 2zE_n N_c b\left(s_{u0} + k\frac{z}{2}\right)$$

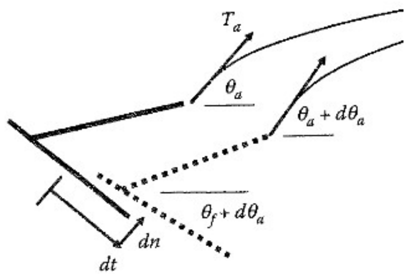
Equilibrium tension at anchor shackle (0° rotation)

$$T_a = N_{e0} s_u A_f$$

Key equation anchor rotation/ padeye angle line

$$\frac{d\theta_a}{dz} = \frac{1}{\theta_a}\left(\frac{E_n N_c b}{N_{e0} A_f} - \frac{k\theta_a^2}{2 s_{ua}}\right)$$

Anchor displacement



$$\Delta z = \Delta t sin\theta_f - \Delta t R_{nt} cos\theta_f$$

$$\Delta x = \Delta t cos\theta_f - \Delta t R_{nt} sin\theta_f$$

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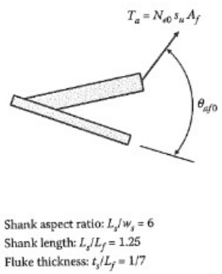
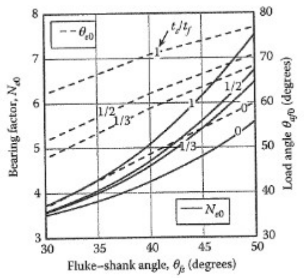
DEA kinematic and holding capacity - Clay

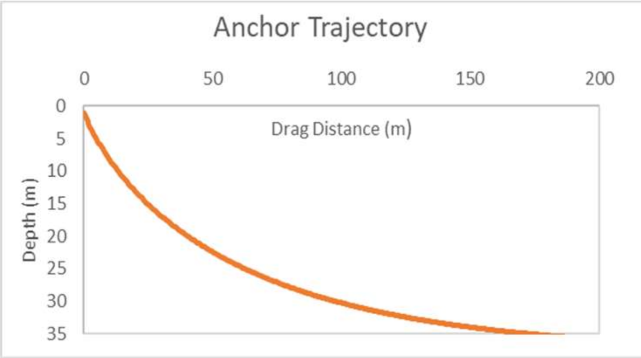
Aubeny and Chi (2010)

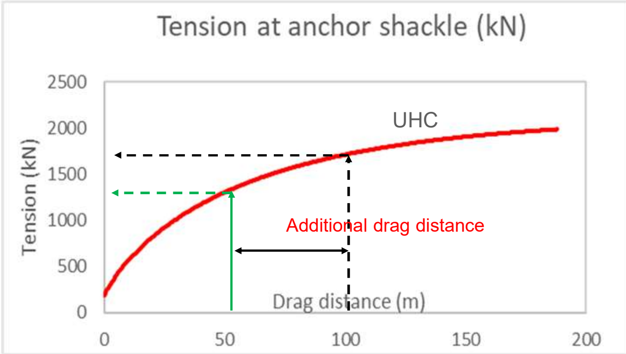
- Full drag distance & penetration prediction
- Ultimate anchor holding capacity at 0° fluke rotation
- Prediction for additional drag distance at operation
- Relatively complex
- Homogenous soft Clay $Su=S_{u0}+K \cdot z$
- N_{e0} bearing factor requires site corelation & depends on multiple variables:

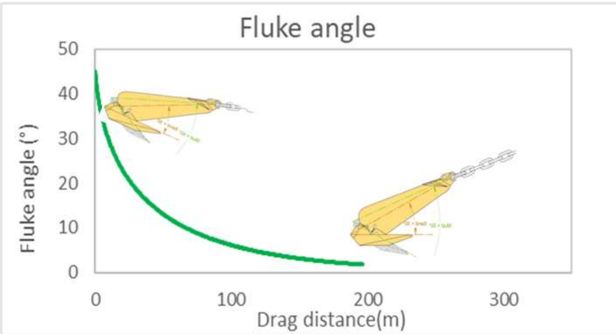
  - Shank thickness, Fluke thickness, fluke shank angle

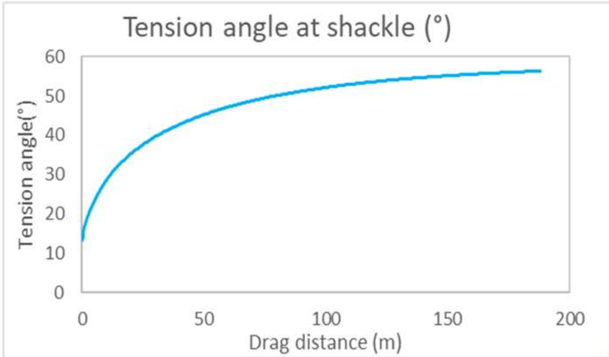








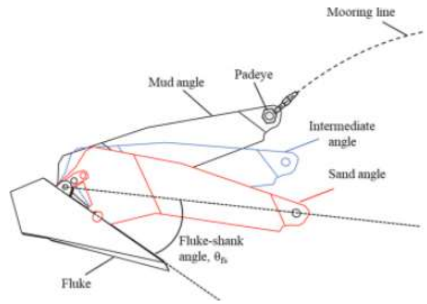




Example using Su=2+1.5z, N_{e0}=5.8, Fluke area 6m², Initial angle θ_f=45°, line diameter=0.076m

Floating Wind Farm
Drag Anchors and Plate Anchors
Recommendations

DEA in Sand and High strength Clay – General recommendations



Sand

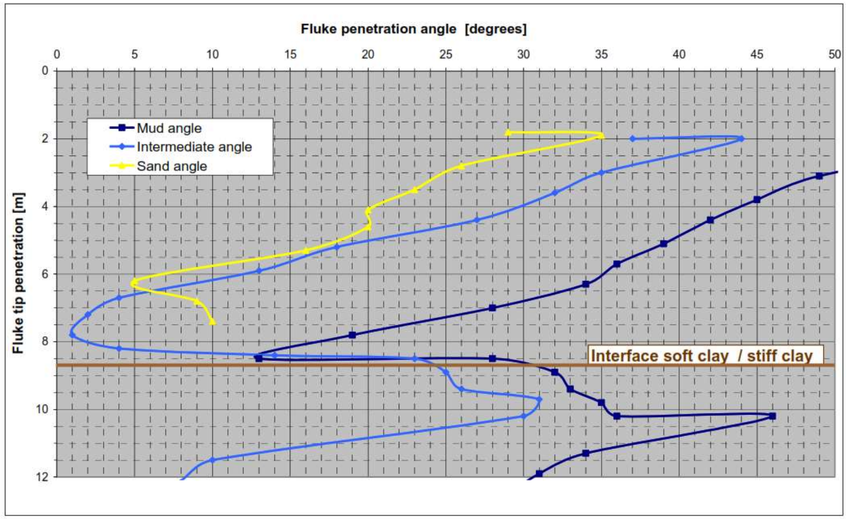
- Analytical predictions similar to clay provided in (*Neubecker and Randolph (1996), Miedema et al (2001) and Liu et al (2010))*
- Shallow penetration expected, fluke ballast is in some cases required
- In very dense sand, penetration = 1 x fluke length and loose sand 2 x fluke length
- General recommendation is at least one fluke penetration to dump scouring effects
- Drag distances are short : ~8 x Fluke length

High strength clays

- Poorly documented
- Adopt a lower fluke shank angle than the one recommended for soft clays

Layered soils

- Sand/Hard clay transitions or soft Clay / Hard clay transitions (slippage risk)



Predicted fluke tip penetration versus fluke penetration angle for BRUCE FFTS Mk4 – OTC 20085

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Drag Anchors and Plate Anchors Recommendations

Characteristic resistance of Fluke anchors

- **The characteristic resistance of DEA at the dip down point is defined as :**

$$R_c = R_{i,c} + \Delta R_{post} + \Delta R_{fric}$$

$R_{i,c}$: Characteristic installation resistance at dip down point

ΔR_{post}: Post installation effects (cyclic effects, set-up, additional drag)

ΔR_{fric} : Frictional resistance chain/seabed along L_s (if no uplift)

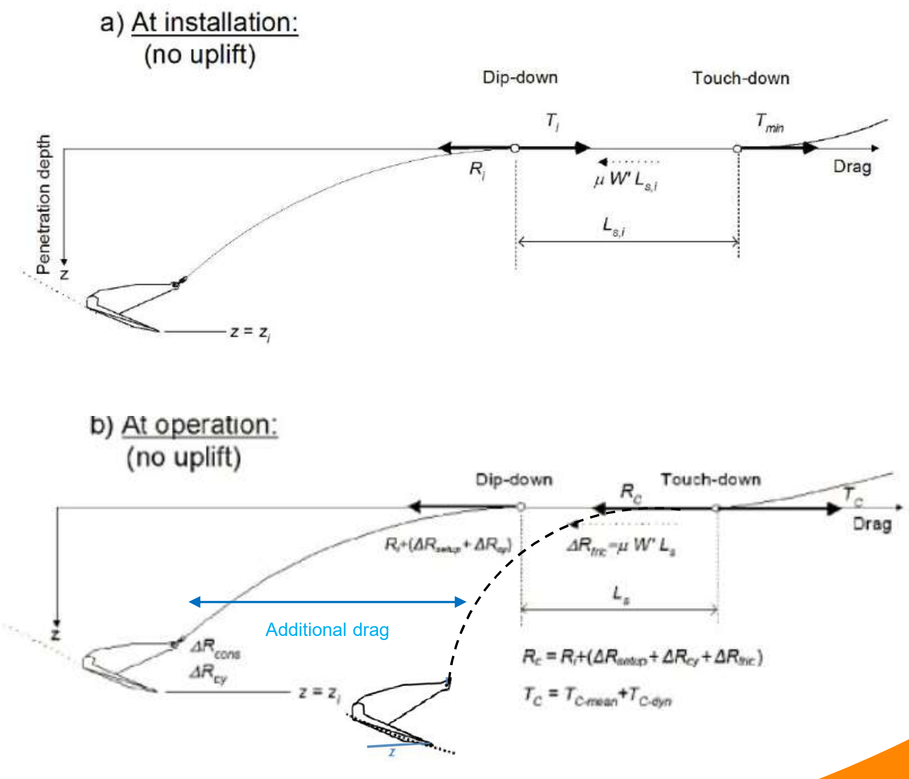
- The characteristic installation resistance is equal to the installation tension (T_i) since measurable and maintained during a sufficient time lapse
- The characteristic resistance with post installation ΔR_{post} effects are :

- **With additional drag**

$$R_c = R_{i,c} + \underbrace{\Delta R_{drag} + \Delta R_{cyc}}_{\Delta R_{post}} + (\Delta R_{fric})$$

- **With no additional drag**

$$R_c = R_{i,c} + \overbrace{\Delta R_{setup} + \Delta R_{cyc}}^{\Delta R_{post}} + (\Delta R_{fric})$$



DNV-RP-E301 (2021) – Tensions at anchor

Floating Wind Farm
Drag Anchors and Plate Anchors
Recommendations

Post Installation effects

Additional drag

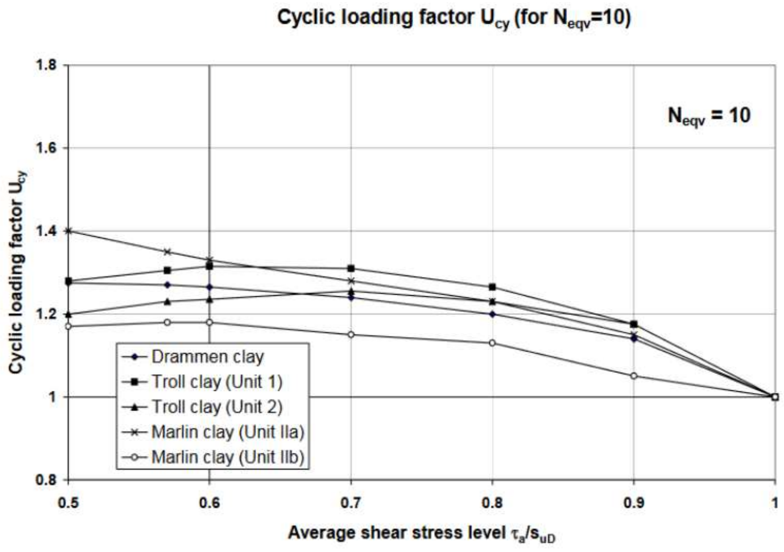
- Allows for lower T_i
- Anchor allowed to penetrate/drag for a design event
- Additional drag mobilizes further resistance (however set-up effects are lost)
- Depending on the project constrains and consequences (soil type & ground uncertainties, mooring configuration, floating wind turbine tolerances)

Cyclic loading effect

- Variation in resistance : combination of rate of loading effects (+) and cyclic degradation effects (-)
- For one way loading the above cumulated effect is (+)
- Special care in highly compressible soils or highly sensitive to cyclic degradation (i.e *carbonate soils*) whose effect can be (-) (*Neubecker et al (2005)*)

Set-up effects (in clay)

- In the direction of the fluke
- Partial remolding (uneven disturbance) : Disturbance Ratio DR=0.5
- Set-up factor U_{setup} f(S_t , DR, t_{setup}, geometry, depth, orientation)



Cyclic loading factor U_{cy} for typical N_{eqv}=10 (Andersen 2004)

$$R_{cy} = R_{i,c} \cdot U_{setup} \cdot U_{cy} = R_{i,c} + \Delta R_{setup} + \Delta R_{cyc}$$

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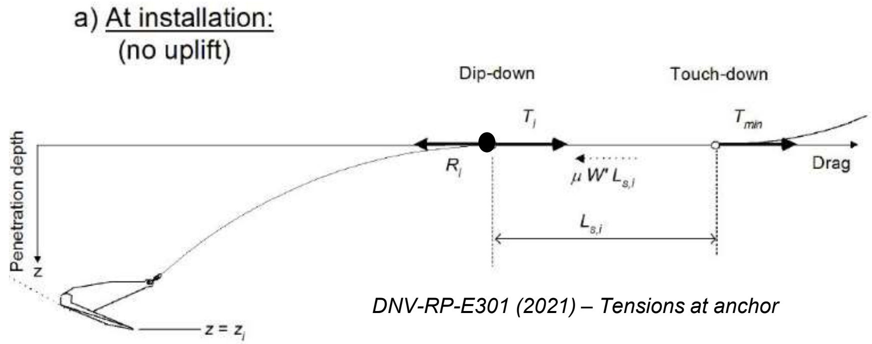
Installation tension and proof tests

Minimum Installation tension T_i

$$T_{i,min} = T_i + \gamma_R \cdot \Delta R_{f,i}$$

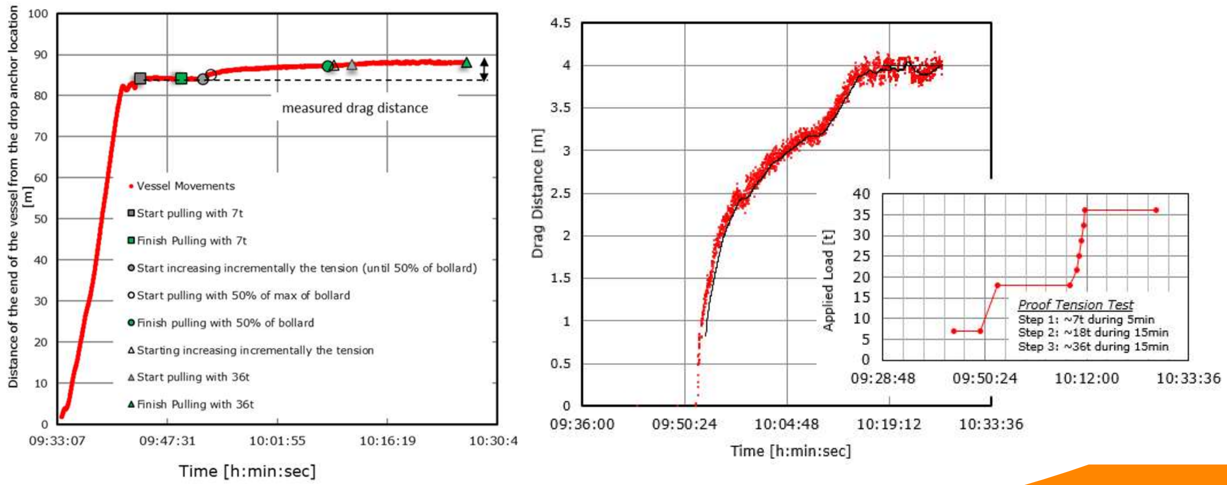
$$\Delta R_{f,i} = \mu \cdot W_l' \cdot L_{s,i}$$

μ = coefficient of seabed friction
W_l' = submerged weight per unit length of anchor line
γ_R = resistance factor



DNV-RP-E301 (2021) – Tensions at anchor

- Minimum tension required at installation to reach the design capacity
- should be applied and maintained for a designated holding period.
- The holding period, influenced by soil type, should not be shorter than 15 minutes
- holding period, any relaxation (i.e. additional drag) should be compensated, and the tension maintained as constant as possible.



Example of proof test – courtesy of Subsea7